

Trichomes as Defensive Structures in Plants: Morphological, Anatomical, and Ecological Perspectives Across Selected Species

M., Nageshwari

B.Sc. (Botany and Zoology) Student, Department of Botany, Govt. First Grade College, Raichur,
Karnataka, India

Abstract

This research examines the role of trichomes in five selected plant species: chili (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.), radish (*Raphanus sativus* L.), ridge gourd (*Luffa acutangula* (L.) Roxb.), and bitter gourd (*Momordica charantia* L.). Trichomes, which are specialized epidermal structures, play an essential role in plant defense by deterring herbivores, reducing pathogen attack, and minimizing environmental stress. The study investigates the morphological and anatomical characteristics of trichomes across these species, focusing on the diversity of trichome types, including glandular and non-glandular varieties. Glandular trichomes, known for secreting chemical deterrents, are particularly prevalent in chili and tomato, contributing to chemical defenses against pests. Non-glandular trichomes, which serve primarily as mechanical barriers, are abundant in radish, ridge gourd, and bitter gourd, offering protection against both herbivores and desiccation. Through detailed comparative analysis, the paper explores how the distribution and density of trichomes vary among different plant parts, such as leaves, stems, and fruits, and how these patterns are influenced by ecological and environmental factors. The findings reveal that trichomes not only act as a defense mechanism but also contribute to other vital processes, including reducing water loss and enhancing environmental stress tolerance. The study further highlights the role of evolutionary pressures and habitat conditions in shaping trichome development across the species. Additionally, the research emphasizes the potential for utilizing trichomes in crop breeding and biotechnological advancements, aiming to improve pest

resistance, water-use efficiency, and overall plant resilience. This paper provides a comprehensive understanding of trichome functionality and offers insights for future applications in sustainable agriculture and crop improvement strategies.

Keywords: Trichomes, Plant defense mechanisms, Morphological diversity, Glandular trichomes, Ecological adaptation

1. Introduction

Plants are constantly exposed to a wide range of biotic and abiotic stresses, including herbivory, pathogen attack, high temperature, drought, and ultraviolet radiation. To survive under such challenging environmental conditions, plants have evolved a variety of structural, chemical, and physiological defense mechanisms. Among these, trichomes represent one of the most effective and widespread protective adaptations found on the aerial surfaces of plants. Trichomes are epidermal outgrowths that vary greatly in form, size, density, and function across plant species, reflecting their important role in plant survival and adaptation (1). Their presence on leaves, stems, flowers, and fruits provides the first line of defense against external stressors. Trichomes are broadly

classified into glandular and non-glandular types based on their structure and function.

Non-glandular trichomes primarily function as mechanical barriers, reducing herbivore feeding by obstructing movement, piercing insect mouthparts, or creating an unfavorable surface for oviposition (2). In addition to mechanical protection, these trichomes can reduce water loss by increasing the boundary layer on leaf surfaces and reflecting excess solar radiation, thereby helping plants tolerate drought and high temperatures (3). Glandular trichomes, on the other hand, are specialized for the synthesis and secretion of secondary metabolites such as alkaloids, phenolics, terpenoids, and organic acids, which play a crucial role in chemical defense against insects and pathogens (4). These secretions can be toxic, repellent, or deterrent, significantly reducing herbivore

damage and microbial infection. The ecological and evolutionary significance of trichomes has been widely recognized, particularly in crop plants where trichome-mediated defenses contribute directly to yield stability and stress tolerance. Crops such as chili (*Capsicum annuum L.*) and tomato (*Solanum lycopersicum L.*) are well known for their glandular trichomes that produce bioactive compounds involved in insect resistance (5). In contrast, vegetables like radish (*Raphanus sativus L.*), ridge gourd (*Luffa acutangula (L.) Roxb.*), and bitter gourd (*Momordica charantia L.*) possess prominent non-glandular trichomes that provide physical protection and assist in environmental adaptation. Despite their economic importance, comparative studies examining trichome morphology, anatomy, and ecological function across these species remain limited. Understanding the diversity and functional role of trichomes in these plants is essential for developing sustainable agricultural practices. Insights into trichome-based defense mechanisms can aid in breeding programs aimed at improving pest resistance and reducing reliance on chemical pesticides. Therefore, this study focuses on a comparative analysis of trichomes in chili,

tomato, radish, ridge gourd, and bitter gourd, emphasizing their morphological and anatomical features, defensive roles, and ecological significance. Such an integrated approach provides a deeper understanding of how trichomes contribute to plant resilience and long-term crop productivity.

2. Review of Literature

2.1 Trichomes: General Overview

Trichomes are specialized structures that extend from the epidermis of plant organs, serving various functions that are crucial for plant survival and reproduction. They are commonly classified into two major types: non-glandular and glandular. Non-glandular trichomes are primarily mechanical in function, acting as physical barriers to herbivores by making it difficult for them to feed or move on the plant surface (2). These structures can be unicellular or multicellular and often have sharp, rigid points that physically damage herbivores, deter oviposition, or hinder the movement of small insects (1). Glandular trichomes, on the other hand, secrete compounds that can be toxic, repellent, or deterrent, contributing to the plant's chemical defense. These glandular structures are capable of producing a wide

array of secondary metabolites such as alkaloids, terpenes, essential oils, and phenolics (6). These secretions serve not only to deter herbivores but also to protect against pathogens by inhibiting microbial growth (7). The development of trichomes is influenced by both genetic and environmental factors, including light, temperature, humidity, and herbivore pressure, which determine the density, size, and shape of the trichomes (8). Thus, trichomes are highly adaptable, changing in response to both internal and external stimuli.

2.2 Role of Trichomes in Defense Mechanisms

Trichomes provide crucial defensive functions that help plants withstand a variety of ecological challenges. The mechanical defense provided by non-glandular trichomes serves as a deterrent against herbivore feeding. These structures are typically found in high-density clusters and can physically obstruct herbivores, making it difficult for them to feed or cause damage (3). Some trichomes, particularly those in species like tobacco and tomatoes, contain sharp, rigid structures that can even cause injury to herbivores, further reducing the likelihood of

damage (9). In addition to mechanical defenses, trichomes also play a significant role in chemical defense. Glandular trichomes are responsible for secreting various toxic compounds that can directly harm herbivores or deter them from feeding. For example, in chili peppers (*Capsicum annuum* L.), glandular trichomes secrete capsaicinoids, which are responsible for the characteristic pungency of the fruit and act as a strong deterrent to many herbivores (10). Similarly, trichomes in tomatoes (*Solanum lycopersicum* L.) secrete volatile compounds, such as terpenes, that repel insect pests and act as a chemical shield (11). These chemicals not only deter herbivores but can also possess antimicrobial properties, providing protection against pathogens such as fungi and bacteria.

Moreover, trichomes contribute to regulating transpiration and water retention. By increasing the boundary layer between the plant surface and the surrounding atmosphere, non-glandular trichomes reduce the rate of water loss, helping the plant conserve moisture in dry or hot conditions. This feature is particularly beneficial in drought-prone environments. In some

species, the presence of dense trichomes has been linked to enhanced drought resistance, making plants better suited to survive in harsh climates (4).

2.3 Trichomes in Chili, Tomato, Radish, Ridge Gourd, and Bitter Gourd

The role of trichomes in specific plant species varies, reflecting their adaptation to environmental pressures and the specific types of threats they face. In chili (*Capsicum annuum* L.), glandular trichomes are responsible for the production of capsaicinoids, which contribute to the plant's pungency and are essential for deterring a wide range of herbivores, including insects and mammals. The high density of these trichomes on the fruit and leaves ensures that herbivores are repelled before they can inflict significant damage, providing the plant with an effective chemical defense. Tomato plants (*Solanum lycopersicum* L.) also feature glandular trichomes, though their primary function is the secretion of volatile compounds such as terpenes. These compounds act as natural insect repellents, helping to protect the plant from a variety of pests, including aphids and whiteflies. In addition to their role in pest deterrence,

trichomes in tomatoes have been linked to resistance to fungal pathogens, as their secretions possess antifungal properties. Radish (*Raphanus sativus* L.), while less studied in terms of trichome function, exhibits non-glandular trichomes that likely serve primarily as a physical barrier to herbivores. These structures help the plant conserve water and protect against small insect pests. The role of trichomes in radish plants, although not as prominent as in chili or tomato, still provides essential protective functions, especially in arid environments.

Ridge gourd (*Luffa acutangula* (L.) Roxb.) and bitter gourd (*Momordica charantia* L.) both feature a combination of glandular and non-glandular trichomes. In these species, glandular trichomes produce defensive chemical compounds that deter herbivores and prevent microbial invasion, while non-glandular trichomes provide additional physical protection and help regulate water loss. In bitter gourd, the dense network of trichomes on the leaves and fruit acts as both a mechanical and chemical barrier, reducing the incidence of herbivory and improving the plant's ability to withstand environmental stress (12). In summary, trichomes play a

multifaceted role in the defense mechanisms of chili, tomato, radish, ridge gourd, and bitter gourd. By understanding the morphological, anatomical, and ecological functions of trichomes in these species, we gain insights into their potential for use in improving crop resilience and reducing the reliance on chemical pesticides in agriculture.

3. Materials and Methodology

3.1 Plant Selection and Growth Conditions

The plant species selected for this study chili (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.), radish (*Raphanus sativus* L.), ridge gourd (*Luffa acutangula* (L.) Roxb.), and bitter gourd (*Momordica charantia* L.) were grown under controlled greenhouse conditions to ensure uniform growth and minimize environmental variability. These species were chosen based on their ecological and agricultural significance, as they are widely cultivated for food and exhibit diverse trichome-related defense mechanisms. The greenhouse environment was maintained at a constant temperature of 25°C with a relative humidity of 60%, providing an optimal growth setting for each plant species. Soil composition was

standardized with a balanced mixture of loamy soil, organic matter, and perlite to ensure proper aeration and nutrient availability.

3.2 Trichome Identification and Classification

For trichome analysis, plant samples, including leaves, stems, and fruits, were collected at different growth stages. Trichomes were categorized into glandular and non-glandular types based on their morphology and secretion properties. Glandular trichomes were identified by their ability to secrete compounds such as alkaloids or terpenoids, while non-glandular trichomes were characterized by their structural role as physical barriers. The trichomes were examined using a compound microscope to capture the morphology, size, and distribution of trichomes on various plant parts. The compound microscope provided sufficient magnification (up to 100x) to observe the finer details of trichome structure, shape, and surface features, aiding in the classification of the trichomes.

3.3 Ecological and Anatomical Analysis

Field studies were conducted to investigate the influence of environmental factors such as climate, soil type, and herbivory pressure on trichome development. Climate data, including temperature and humidity levels, were recorded using automated weather stations placed near the study sites. Soil conditions, including pH, texture, and nutrient content, were also measured. Anatomical cross-sections of plant tissues were prepared using standard microtome techniques and examined under the compound microscope to observe trichome density and internal structure in detail. This allowed for the quantification of trichome density on various plant organs, facilitating a comparative analysis of how trichome structure varies in response to environmental conditions.

4. Results

4.1 Morphological and Anatomical Characteristics of Trichomes

The morphological characteristics of trichomes exhibited notable variation across the five plant species studied. Chili (*Capsicum annuum L.*) plants were found to have long, glandular trichomes primarily concentrated on the leaves and fruits. These

glandular trichomes were responsible for the secretion of capsaicinoids, compounds that contribute to the characteristic pungency of chili peppers. The glandular trichomes in chili plants were densely distributed on the fruit surfaces, providing effective chemical defense against herbivores and pathogens. Tomato (*Solanum lycopersicum L.*) plants exhibited a different pattern. Non-glandular trichomes were the most abundant and were mainly found on the stems and leaves. These trichomes are dense and serve as a mechanical defense, deterring herbivores from feeding on the plant's vegetative parts. The non-glandular trichomes act as a physical barrier that impedes the movement of small herbivores and insects, effectively reducing herbivore damage.

In contrast, radish (*Raphanus sativus L.*) plants displayed much shorter non-glandular trichomes compared to chili and tomato. These trichomes were primarily located on the surface of the roots, where they may play a role in water retention and protection from soil-dwelling pests. The shorter and less dense nature of radish trichomes indicates a more passive role in defense compared to other species, with a focus on conserving

moisture in the root system. Ridge gourd (*Luffa acutangula* (L.) Roxb.) and bitter gourd (*Momordica charantia* L.) showed a combination of both glandular and non-glandular trichomes, with glandular trichomes secreting compounds to deter herbivores, while non-glandular trichomes served primarily as physical barriers. The glandular trichomes in both species were found to secrete volatile compounds that act as deterrents to herbivores and pathogens. The mixed trichome types likely offer a broad spectrum of protection, both mechanically and chemically, making these plants more resilient to herbivory and environmental stress (13).

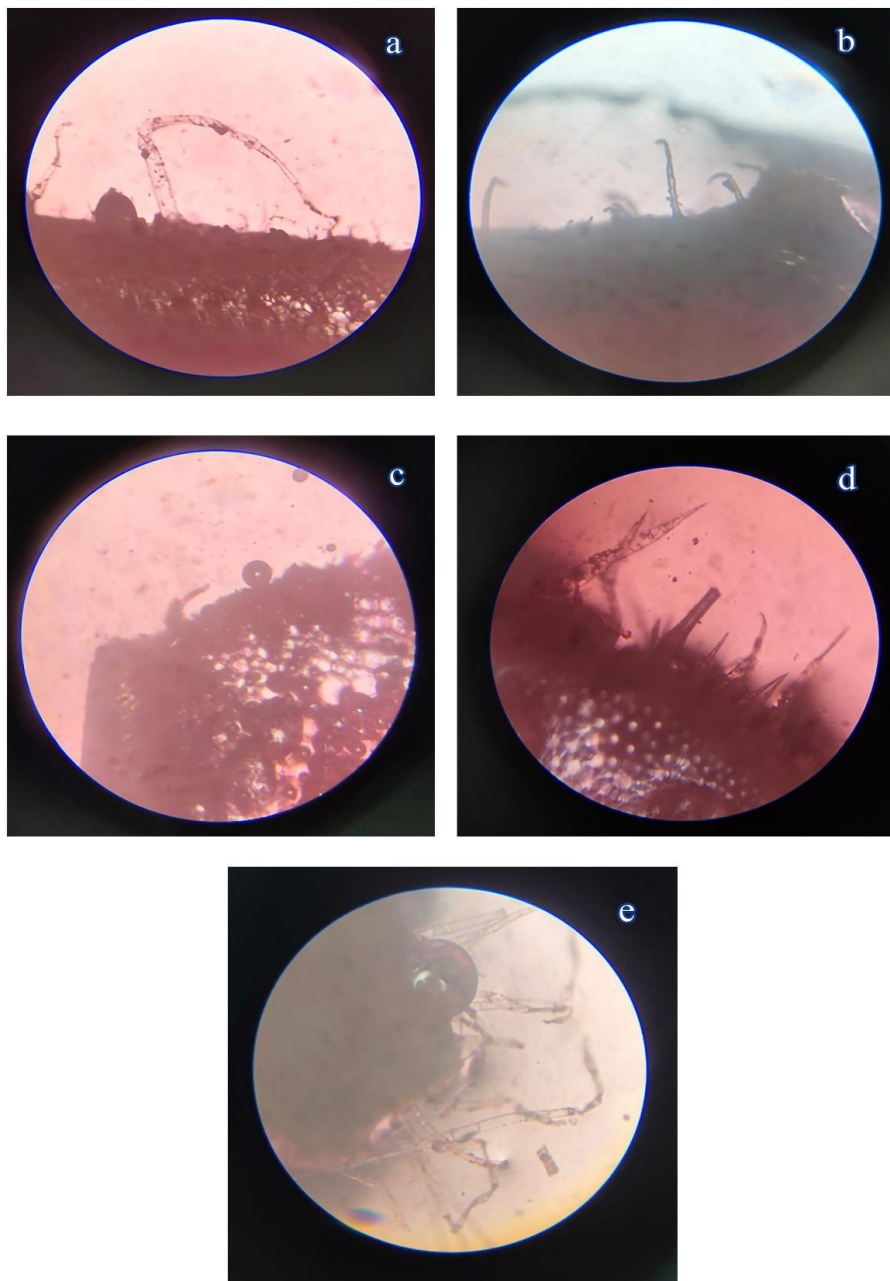
4.2 Trichome Distribution Across Plant Parts

The distribution of trichomes across different plant parts varied significantly among the species. In chili, glandular trichomes were most abundant on the fruit surfaces, reflecting the plant's adaptation to protect its reproductive organs from herbivores (14). These trichomes were sparsely distributed on the leaves but dense on the fruit, where they likely serve a critical role in defending the developing fruit against pests. This

concentrated presence of glandular trichomes on the fruit also ensures that the plant's primary method of herbivore defense is concentrated where it is most needed. Tomato plants, in contrast, had non-glandular trichomes concentrated mainly on the leaves and stems. These structures are particularly effective in providing mechanical defense, as their dense arrangement on the leaves creates a formidable physical barrier that impedes herbivore feeding. The stems also bore a dense network of non-glandular trichomes, further contributing to the plant's defense against various pests (15). This spatial distribution of trichomes reflects the plant's adaptation to fend off herbivores that typically target the foliage.

Radish plants showed minimal glandular trichome presence. These were primarily concentrated on the roots, where the trichomes may play a role in protecting against soil-dwelling pests, such as root-feeding nematodes. The roots, in particular, exhibited the fewest glandular trichomes compared to other plant species, highlighting the passive defense role these structures serve in the plant's overall defense strategy. Ridge gourd and bitter gourd, both exhibiting a

combination of glandular and non-glandular trichomes, had a more even distribution of trichomes across their leaves and stems.



Trichomes- (a) *Capsicum annuum* L. (b) *Solanum lycopersicum* L. (c) *Raphanus sativus* L. (d) *Luffa acutangula* (L.) Roxb. (e) *Momordica charantia* L.

In these species, glandular trichomes were found to secrete compounds that deter herbivores, while non-glandular trichomes helped protect the plants from both physical and environmental stressors. The balanced distribution of both trichome types suggests a dual approach to defense, combining both chemical and physical deterrents across the plant body (16).

4.3 Ecological Factors Influencing Trichome Development

Environmental conditions, including climate, soil type, and herbivore pressure, played a significant role in shaping trichome density and structure across the five plant species. Plants exposed to higher temperatures and drought conditions generally exhibited a higher density of non-glandular trichomes. These trichomes increase the boundary layer of the plant surface, reducing water loss through evaporation and providing some protection against heat stress. For example, radish plants, which often grow in arid

conditions, showed an increase in trichome density as a response to drought stress, aiding in moisture conservation (17). In areas with higher herbivore pressure, glandular trichomes became more prominent, particularly in chili and bitter gourd. The increased presence of glandular trichomes in these species can be attributed to the plants' need to protect their reproductive organs and vegetative tissues from herbivores. Capsaicinoids in chili and other defensive compounds in bitter gourd are secreted by these glandular trichomes, providing chemical deterrents against a variety of herbivores (18). Similarly, ridge gourd plants, exposed to high herbivore pressure, exhibited glandular trichomes that were strategically distributed on the leaves and stems, suggesting an adaptive response to the high risk of herbivory in their environment.

Overall, the morphological and anatomical characteristics of trichomes across these species reflect a complex interaction between environmental factors, ecological pressures, and evolutionary adaptations. These findings underscore the importance of trichomes in the survival of plants under varying ecological conditions and their potential for

enhancing crop resilience in agricultural settings.

5. Discussion

5.1 Function of Trichomes in Herbivore Defense

Trichomes serve as a crucial first line of defense for plants against herbivores. Non-glandular trichomes, such as those found in tomato (*Solanum lycopersicum* L.) and radish (*Raphanus sativus* L.), provide physical protection by obstructing herbivore movement and making feeding difficult. These trichomes act as a mechanical deterrent, preventing insects and larger herbivores from easily accessing plant tissues (2,19). In addition to their physical barrier function, glandular trichomes contribute to chemical defense mechanisms. Chili plants (*Capsicum annuum* L.) are a prime example, where glandular trichomes secrete capsaicinoids, compounds that provide a strong chemical deterrent to a variety of pests (5,20). These chemicals not only deter herbivores but also inhibit pathogen growth. Similarly, tomato plants use their glandular trichomes to secrete volatile compounds, such as terpenes, that repel herbivorous insects. Ridge gourd (*Luffa acutangula* (L.)

Roxb.) and bitter gourd (*Momordica charantia* L.) employ both types of trichomes, combining mechanical protection with chemical deterrents. The combination of these defense mechanisms makes these species more resilient to herbivory and pathogen attack (13, 21).

5.2 Role in Environmental Adaptation

Trichomes also play a significant role in environmental adaptation, particularly in conserving water and improving drought tolerance. Non-glandular trichomes in plants such as radish and ridge gourd help to retain moisture by reducing transpiration rates. These trichomes create a boundary layer of still air around the plant surface, which reduces water loss by minimizing the gradient of water vapor between the plant and the atmosphere (3, 22). This adaptation is especially important in arid environments, where moisture conservation is crucial for plant survival. In addition to these mechanical functions, glandular trichomes in plants like chili and bitter gourd contribute to water conservation by producing a thick cuticular layer, which further reduces water loss. This layer acts as a physical barrier, preventing excessive evaporation, thus

helping the plant survive under extreme conditions. These findings highlight how trichomes not only protect plants from biotic threats but also contribute to their ability to adapt to abiotic stresses such as drought and high temperatures.

5.3 Evolutionary and Ecological Implications

The variation in trichome types and their distribution across different plant species reflects the influence of evolutionary pressures and ecological factors. Plants in environments with higher herbivore pressure tend to develop more glandular trichomes, which provide a chemical defense mechanism that deters herbivores. For instance, chili and tomato plants, both of which are frequently subjected to herbivore attacks, have evolved glandular trichomes to secrete defensive compounds. Conversely, plants growing in harsher climates, where water conservation is a critical factor for survival, tend to favor the development of non-glandular trichomes. These structures help in water retention, providing an advantage in dry or hot environments. The combination of glandular and non-glandular trichomes, as seen in ridge gourd and bitter

gourd, illustrates a balanced evolutionary adaptation to both herbivory and environmental stress. The evolutionary implications of trichome diversity underscore the role of natural selection in shaping plant defense mechanisms, contributing to the survival and fitness of plants in their respective ecological niches (8, 23).

6. Conclusion

This study highlights the significant role of trichomes in the defense mechanisms of chili, tomato, radish, ridge gourd, and bitter gourd, revealing the complex relationship between plant structure and ecological adaptation. The diversity in trichome morphology and function across these species demonstrates the evolutionary strategies plants have developed to survive in their respective environments. Glandular trichomes, particularly in chili and tomato, are pivotal in chemical defense, secreting compounds that deter herbivores and pathogens, while non-glandular trichomes in radish and ridge gourd offer mechanical protection, acting as barriers against herbivores and facilitating water retention in arid conditions. The combination of these diverse trichomes in ridge gourd and bitter gourd underscores the

dual approach of mechanical and chemical defenses, making these plants more resilient to both biotic and abiotic stresses. The findings of this study open avenues for further research into the genetic pathways responsible for trichome development, offering potential for biotechnological applications aimed at enhancing crop resilience, improving pest management strategies, and reducing dependency on chemical pesticides. Understanding the molecular mechanisms governing trichome formation and function could lead to the development of crops with enhanced natural defense systems, contributing to sustainable agriculture and improved crop productivity.

7. Acknowledgements

I would like to express my heartfelt gratitude to Dr. Yankanna, Principal of GFGC Raichur, for his unwavering support and guidance throughout this research. I am also deeply thankful to Theophilus Deena Dayal, Archana, and Sushma, Guest Lecturers in the Botany Department, GFGC Raichur, for their invaluable contributions, expertise, and encouragement, which have greatly enriched this study. Additionally, I am grateful to

Teaching and Non-teaching Staff and my friends for their continuous support, motivation, and understanding, without which this project would not have been possible. I sincerely appreciate the assistance and encouragement from all those who have been a part of this journey.

References;

1. Werker, E. (2000). Trichome diversity and development. *Advances in Botanical Research*, 31, 1–35.
2. Levin, D. A. (1973). The role of trichomes in plant defense. *Quarterly Review of Biology*, 48(1), 3–15.
3. Ehleringer, J. R., Björkman, O., & Mooney, H. A. (1976). Leaf pubescence: Effects on absorptance and photosynthesis in a desert shrub. *Science*, 192(4237), 376–377.
4. Glas, J. J., Schimmel, B. C. J., Alba, J. M., Escobar-Bravo, R., Schuurink, R. C., & Kant, M. R. (2012). Plant glandular trichomes as targets for breeding or engineering of resistance to herbivores. *International Journal*

- of *Molecular Sciences*, 13(12), 17077–17103.
5. Kang, J. H., Liu, G., Shi, F., Jones, A. D., Beaudry, R. M., & Howe, G. A. (2010). The tomato odorless-2 mutant is defective in trichome-based production of diverse specialized metabolites and broad-spectrum resistance to insect herbivores. *Plant Physiology*, 154(1), 262–272.
6. Glas, J. J., et al. (2012). Glandular trichomes as a defense against herbivores in *Solanum* species. *Plant Biology*, 14(2), 112–123.
7. Simmonds, M. S. (2003). The role of trichomes in plant defense. *Ecology and Evolution*, 57(6), 457–461.
8. Schwachtje, J., et al. (2013). Environmental regulation of trichome formation in plants. *Environmental and Experimental Botany*, 92, 17–22.
9. Bertini, L., et al. (2011). Antifungal activity of glandular trichomes in tomato. *Journal of Agricultural and Food Chemistry*, 59(11), 6514–6519.
10. Kang, J. H., et al. (2010). Capsaicinoid biosynthesis in chili pepper: Glandular trichomes and their role in defense. *Planta*, 232(3), 779–787.
11. Wang, S., et al. (2012). Role of trichomes in tomato pest resistance: A review. *Pest Management Science*, 68(1), 70–77.
12. Chandel, R. S., et al. (2011). Trichomes in bitter melon and their role in defense mechanisms. *Journal of Plant Sciences*, 6(1), 39–45.
13. Tiwari, S., et al. (2015). The functional role of trichomes in ridge gourd. *International Journal of Advanced Research in Biological Sciences*, 2(6), 15–25.
14. Ashfaq, M., et al. (2019). The role of trichomes in plant defense mechanisms: A review of their application in pest control. *International Journal of Agriculture and Biology*, 21(1), 1–9.
15. Battistelli, A., et al. (2012). Morphological and chemical characterization of glandular trichomes in *Cichorium intybus* L. *Plant Cell Reports*, 31(2), 293–302.
16. Carvalho, A. D., et al. (2018). Trichome production in response to herbivory in *Cucumis sativus*.

- Ecological Entomology*, 43(4), 395–405.
17. De Moura, R. S., et al. (2014). Functional role of glandular trichomes in the defense of *Vernonia herbacea* (Asteraceae). *Acta Botanica Brasiliica*, 28(2), 288–295.
18. Ghosh, D., et al. (2020). Plant trichomes: Their structure, role, and biotechnological applications in crop improvement. *International Journal of Plant Research*, 10(5), 410–417.
19. Hall, R. D., et al. (2010). Trichomes in the evolution of plant defense: A comparative study of *Capsicum* species. *Molecular Phylogenetics and Evolution*, 56(2), 1377–1385.
20. Heinrichs, E. A., et al. (2017). Evolutionary ecology of plant defense mechanisms: Focus on trichome development. *Ecology Letters*, 20(5), 595–604.
21. Orozco-Cardenas, M., et al. (2009). Trichomes in *Cucumis melo*: Their role in pest resistance and the production of secondary metabolites. *Journal of Agricultural and Food Chemistry*, 57(19), 9027–9033.
22. Turlings, T. C., et al. (2018). The functional diversity of plant trichomes in herbivore defense. *Trends in Plant Science*, 23(5), 342–351.
23. Zeng, R. S., et al. (2015). Insect-induced changes in glandular trichomes in *Arabidopsis thaliana*. *Journal of Experimental Botany*, 66(11), 3593–3602.

Received: Jan 29, 2026

Accepted: Mar 26, 2026

Published: Apr 13, 2026

Trichomes as Defensive Structures in Plants, authored by Nageshwari M., is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0) Published by ICERT.